International Journal of Heat and Mass Transfer 108 (2017) 1764–1774

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Elastic turbulence influences and convective heat transfer within a miniature viscous disk pump

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ARTICLE INFO

Article history:
Received 11 October 2016
Received in revised form 18 December 2016
Accepted 20 December 2016
Available online 20 January 2017

Keywords:
Elastic turbulence
Micro-scale-flow
Elasticity transition
Thermal transport
Heat transfer

ABSTRACT

Elastic turbulence is employed within the present investigation to enhance convective heat transfer at very small scales and at very low Reynolds numbers. A miniature viscous disk pump or VDP is utilized to investigate flow and heat transfer, where the latter are based upon energy balance measurements which utilize the mixed-mean temperature at the inlet and outlet of the viscous disk pump passage. The overall heat transfer rate is determined based upon a constant surface temperature thermal boundary condition, and upon a log-mean-temperature difference approach. The VDP operates at rotation speeds of 500 RPM, 1000 RPM, 1500 RPM, 1800 RPM, and 2000 RPM, which produce overall shear rates across the flow cross section of 146.05 1/s, 292.1 1/s, 438.15 1/s, 525.78 1/s, and 584.2 1/s. A channel depth of 640 μm is employed. Elastic turbulence is induced by adding polyacrylamide to water solutions with 65% sucrose by mass. Significant enhancements of mixing and transport are observed, which are associated with the onset and development of elastic turbulence. Such behavior is verified, relative to an increased viscosity Boger fluid, using flow visualization results, rheometer viscosity variations with shear rate, and increases of overall magnitudes of convective heat transfer coefficient, which are augmented by as high as 240%. These comparisons are assessed relative to the Newtonian Boger fluid (which generally does not change viscosity as shear rate varies) at the same rotation speed, shear rate, flow passage height, and inlet temperature. As polymer concentration increases, elastic turbulence effects become more pronounced, and heat transfer coefficient magnitudes increase. This occurs such that Nusselt number ratios are strongly correlated with the mean-square magnitude of scalar temperature fluctuations at the outlet of the VDP. As a result, remarkable heat transfer coefficient enhancements due to elastic turbulence are demonstrated.

1. Introduction

Various micro-scale devices have been investigated during recent decades, which generally operate at very low Reynold numbers. However, enhancements of convective heat transfer are a challenge to implement at such microscopic scales. The present investigation considers the use of elastic turbulence to enhance the fluid mixing, thermal transport, and heat transfer at very low Reynold numbers within such arrangements.

Elastic turbulence is excited by non-linear mechanical stresses, without significant inertial effects, at low Reynold numbers. The non-linear mechanical properties of the polymer solution generally lead to flow mixing and chaotic motions, referred as the Weissenberg instability [1]. When managed in an appropriate fashion, such polymer additives can lead to sharp growth in local elastic stress magnitudes, and local and global transition to elastic turbulence. Growth of local stresses depends upon experimental configuration, shear rate, polymer type, polymer concentration, and other parameters. The stress growth then stretches the polymer, leading to local secondary flow, increased mixing, and chaotic fluid motions [1]. This phenomenon is most often observed when the Weissenberg number is greater than an onset value, which depends upon polymer type, polymer concentration, experimental configuration, and other parameters.

A variety of different configurations are employed in recent investigations. For example, Grosiman and Steinberg [1] describe elastic instability generated within the viscoelastic fluid which augments mixing and transport within curved channels. Nashie et al. [2] numerically consider aspects of diffusion and flow behavior within a circular body of revolution. Observed are spatial chaos due to non-linear dynamics, which is linked to increased mixing and diffusion. Berti and Boffetta [3] and Berti et al. [4] consider elastic turbulence using two-dimensional Kolmogorov flow. Their

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.12.075
0017-9310/

Nomenclature

A	cross-sectional area of the working fluid within the channel
c	specific heat capacity
D	perimeter where the constant temperature boundary condition is applied
h	heat transfer coefficient
k	thermal conductivity
L	characteristic length
Lc	circumferential flow passage length
m	concentration ratio power exponent
Nu	Nusselt number for sucrose and polymer solutions
Nu_0	Nusselt number for Boger fluid solutions with sucrose only
P	channel perimeter
P	static pressure
$\dot{q}$	heat flux
r	radial coordinate
R_1	inner radius of the flow passage
R_2	outer radius of the flow passage
Re_{ETC}	elastic turbulence concentration Reynolds number
s	gap height of the viscous disk pump flow passage
t	static temperature
t'	temperature fluctuation at the outlet of flow passage
t_m	local mixed-mean temperature
t_0	local surface temperature
T	non-dimensional temperature
T_{out}	mixed-mean temperature at the outlet of the flow passage
T_{in}	mixed-mean temperature at the inlet of the flow passage
T_s	surface temperature
V	spatially-averaged velocity
v_θ	local circumferential component of velocity
v_r	local radial component of velocity
v_z	local normal component of velocity
z	normal coordinate

Superscript

—	time-averaged

Greek symbols

$\dot{\gamma}$	local fluid shear rate
μ	absolute viscosity
ρ	fluid density
ρ_c	polyacrylamide concentration in parts per million
ρ_{co}	concentration constant
ω	rotational speed of the disk, $2\pi\Omega/60$
Ω	dimensional rotational speed of the disk, RPM
θ	circumferential coordinate
$\Delta\theta$	circumferential span between two angular locations

results show viscoelastic flows which demonstrate increasing mixing features and complexity with very small inertial non-linearity. Schiamberg et al. [5] describe experimental results which show sets of secondary flows with negligible inertial effects for flow between parallel plates. Li et al. [6] create chaotic fluid in microchannels with viscoelastic surfactant solutions at very low Reynold numbers. According to these investigators, elastic turbulence is induced by the viscoelasticity of the solution when strain is applied by curvilinear streamlines.

Experiments which consider the fluid mechanics and heat transfer behavior of viscoelastic aqueous polymer solutions in channel flow are described by Hartnett and Kostic [7] and by Hartnett [8]. For turbulent and laminar flows, such viscoelastic fluids show high heat transfer coefficients which are due to secondary motions, which are tied to unequal normal stresses within the viscoelastic fluids. Numerical investigations are described by Zhang et al. [9,10] which address connections between elastic turbulence and enhancement of local flow mixing. Abed et al. [11], and Whalley et al. [12] describe enhancements in flow mixing from elastic turbulence which often result in enhancements of convective heat transfer rates, when compared for the same configuration and same experimental conditions. Of these investigations, Abed et al. [11] experimentally consider convective heat transfer and fluid flow within a square cross-section serpentine channel with both polymeric viscoelastic fluids, and with constant-viscosity Newtonian Boger solutions as a basis of comparison. According to these investigators, convective heat transfer is enhanced by as much as 380% for higher polymer solutions and 200% for low polymer concentrations. Another recent investigation which considers elastic turbulence with heat transfer is described by Traore et al. [13]. Results show an increase in heat transfer efficiency within a von Karman flow with elastic turbulence, which illustrates efficient transport of heat in fluid media at low Reynolds numbers.

Within the present investigation, a miniature viscous disk pump (VDP) [14,15] is utilized for experimental study of the effects of elastic turbulence with heat transfer. The experiment is undertaken using a viscoelastic solution with polyacrylamide, and 65% sucrose. Used as a basis of comparison is an increased-viscosity Newtonian Boger fluid (which generally does not change viscosity as shear rate varies), which is created with sucrose, but without any type of added polymer. Comparisons between the two types of fluids are generally undertaken at the same rotation speed, shear rate, flow passage height, and inlet temperature. Because such Boger fluids are associated with a constant viscosity that is independent of shear rate [16], associated results show distinctive different results, relative to elastic turbulence flows. With the present VDP arrangement, the flow passage height is 640 μm, and rotation speed, Ω, ranges from 100 RPM to 2000 RPM. Heat transfer measurements are based upon energy balance considerations, which utilize the mixed-mean temperature at the inlet and outlet of the viscous disk pump passage. The overall heat transfer rate is determined based upon a constant surface temperature thermal boundary condition, and upon a log-mean-temperature difference approach. The thermal boundary conditions at the side walls of the VDP passage are maintained at constant temperature, and whereas the rotating disk is adiabatic. Included are flow visualization results, variations of shear stress, strain rate, and viscosity, spatially-averaged heat transfer coefficients, and spatially-averaged Nusselt numbers. Overall enhanced thermal transport and convective heat transfer rates due to elastic turbulence are illustrated by the data. As such, the present investigation provides new insight into the effects of elastic turbulence on convective heat transfer, within an environment which has never before been employed for this purpose.

2. Viscous disk pump configuration

The viscous disk pump or VDP experimental apparatus is composed of a spinning disk and a C-shaped channel with a fluid inlet port and a fluid outlet port, located at the two ends of the C-shaped channel. Details regarding these different items are provided by